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Analysis of Interstellar Cloud Structure Based on IRAS Images
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The goal of this project was to develop new tools for the analysis of the structure of densely sampled maps of interstellar star-forming regions. A particular emphasis was on the recognition and characterization of nested hierarchical structure and fractal irregularity, and their relation to the level of star formation activity. The panoramic IRAS images provided data with the required range in spatial scale, greater than a factor of 100, and in column density, greater than a factor of 50.

In order to construct densely sampled column density maps of star-forming clouds, column density images of four nearby cloud complexes were constructed from IRAS data. The regions have various degrees of star formation activity, and most of them have probably not been affected much by the disruptive effects of young massive stars. The largest region, the Scorpius-Ophiuchus cloud complex, covers about 1000 square degrees (it was subdivided into a few smaller regions for analysis). Much of the work during the early part of the project focused on an 80 square degree region in the core of the Taurus complex, a well-studied region of low-mass star formation.

The primary drawback to using the IRAS data for this purpose is that it contains no velocity information, and the possible importance of projection effects must be kept in mind. Destriped 60 μm and 100 μm IRAS images were obtained from IPAC. The effective resolution is estimated at 2-3 arcmin. Subtraction of galactic emission was performed by fitting two-dimensional polynomials to a number of low-intensity spots on each image, or a cosecant function. For each pixel the dust temperature was taken as the color temperature derived from the observed 60 μm/100 μm flux ratio, assuming a λ^{-n} wavelength dependence of the far infrared emissivity. The 100 μm optical depth could then be derived from the Planck function using the observed 100 μm intensity. Assuming that the warm dust fraction is a constant, as suggested by other work and by the extensive comparisons mentioned below, the 100 μm optical depth is proportional to the total column density of gas. It was found that the resulting *relative* column density map (the absolute scale of the column densities is irrelevant for the present discussion) was virtually independent of the choice of emissivity law for $n = 1$ and 2, and also was not sensitive to different choices of background subtractions, except for the smallest optical depths.

The validity of the derived column density structures was checked by comparison of various higher-column density ($0.5 \lesssim A_V \lesssim 5$) subregions of the Taurus map with gray scale representations of extinction maps for the dark clouds Heiles Cloud 2(L1534 region), L1495, L1506, L1529, and L1539, and with ^{13}CO maps for Heiles Cloud 2, B216-217-218, and B18 (=L1529 region). The agreement between these maps is for the most part very good, and in fact the pixel-to-pixel noise level appears significantly smaller in the IRAS structure, especially compared to the extinction maps. One disagreement appeared to occur in the core of the L1495 cloud, but it turns out that the ^{13}CO and extinction are saturated there; the $C^{18}O$ maps of this region is in good agreement with the τ_{100} structure, showing that the IRAS data can be used to probe column densities as large as $A_V \approx 10$ mag, even when there is no internal heat source. Much of the lower-column density structure can be seen by careful inspection of POSS plates. These comparisons, along with independent comparisons of τ_{100} with ^{13}CO column densities and A_V by others, demonstrates the ability of IRAS to probe the relative column density structure over a range of at least a factor of 50 in column density. The only major exceptions occur around the locations of embedded IRAS point sources, where the column densities come out very small. This effect is due to temperature gradients along the lines of sight to the point sources, which cause an overestimate of the appropriate mean temperature and an underestimate of the optical depth. These stellar heating regions can be easily recognized as small dark circular disks in the column density image. Although the effect is minor for Taurus, it should be much more serious in regions with massive star formation.

The main conclusion to be drawn from the resulting image is that, when viewed with large dynamic range in spatial scale and column density, one sees complex, irregular, interconnected structure on all scales, with filaments, chains, tendrils, and cirrus-like structure present. This structure does not resemble the ideas of quasi-static evolution of virialized "clouds" or "clumps" popular in current models, bu instead suggests a more dynamically active organizational process.

In fact, the irregularity and continuity of structure makes it difficult to clearly identify any separate entities which correspond to discrete "clouds," although of course regions with various density contrasts and forms can be operationally distinguished. These ideas and their implications were discussed in the review paper "Perception of Interstellar Structure: Facing Complexity," published in the book *Physical Processes in Fragmentation and Star Formation* (ed. R. Capuzzo-Dolcetta *et al.*, pp. 151-177).

While the visual impression of a densely sampled map of a star-forming region can be quite informative, it is of obvious interest to develop quantitative descriptors of structure which can be used to directly compare the observed structure with future numerical hydrodynamic simulations of large spatial dynamic range. In the past, most empirical studies have concentrated on estimating total or average properties for an entire region and cataloguing and searching for correlations between the properties of operationally defined clouds within the mapped region, but not on characterizing the spatial structure itself.

One of the characteristic features of complex systems is hierarchical structure, which is apparent in comparisons of maps of interstellar structures at different resolutions and has figured prominently in many older theoretical discussions of fragmentation. The recognition and description of a hierarchical spatial structure is a problem which has apparently not been discussed in the literature. for interstellar structures which can only be viewed as two-dimensional projections, the difficulties are magnified by the fact that projection will make a random three-dimensional distribution of density enhancements with a variety of scales appear somewhat hierarchical, while even a strictly hierarchical three-dimensional structure will appear more randomized due to the effects of projection.

With these considerations in mind, a new method of image analysis, called "structure tree analysis" was designed to recognize and characterize complex structure, especially hierarchical structures, in a manner well-suited for comparison of observations with theory.

A structure tree is a simplified "stick man" or "primal sketch" representation of the intensity structure of an image which has been partitioned into "clouds." The essential feature of the representation is that it retains the spatial relations of the component clouds, in particular their lineage, while disregarding the information concerning the sizes and shapes of the clouds. After developing an efficient algorithm for structure tree construction, we found that linear combinations of structure tree statistics can discriminate between images of projected hierarchical (multiply nested) and random three-dimensional simulated collections of clouds constructed on the basis of observed interstellar properties, and even intermediate systems formed by combining random and hierarchical simulations. For a given structure type, the method can distinguished between different subclasses of models with different parameters and reliably estimate their hierarchical parameters: average number of children per parent, scale reduction factor per level of hierarchy, density contrast, and number of resolved levels. When applied to the IRAS column density image of the Taurus complex, moderately strong evidence for a hierarchical structural component was found, and parameters of the hierarchy, as well as the average volume filling factor and mass efficiency of fragmentation per level of hierarchy, were estimated. The finding of nested structure contradicts models in which large molecular clouds are supposed to fragment, in a single stage, into roughly stellar-mass cores. This work was published in *The Astrophysical Journal*, **393**, pp. 172-187 (1992).

The latter part of the grant period was devoted to constructing and analyzing column density maps constructed from 27 BIGMAP IRAS images, which were mosaicked into four regions containing low-mass star-forming cloud complexes: Taurus, R Corona Australis, Chameleon/Musca, and Ophiuchus/Scorpius/Lupus. The four regions were subdivided into 11 subregions, distinguished on the basis of visual appearances for study.

The work focused on a search for multifractal scaling and universality, characteristics commonly found for complex systems, low-dimensional chaotic systems, and in critical phenomena. "Multifractal scaling" means here that the column density structure represents an interwoven set of scaling subsets with a range of dimensions. Surprisingly, all subregions with adequate data were found to exhibit well-defined multifractal scaling. However, the corresponding spectrum of singularities, or $f(\alpha)$ curves, show a range of forms, which implies that the column density structures do not form a universality class, in contrast to indications for incompressible turbulence and many other "complex systems."

We have also begun to investigate the "wavelet transform" of the IRAS column density maps as an alternative method for compressing the structure. The wavelet transform is the convolution of the image intensity pattern with an "analyzing wavelet" which acts essentially as a notch filter that highlights regions of a given scale. This representation of an image gives the transform intensity in a three-dimensional space, two of whose axes are spatial, the other measuring scale, and is typically a tree-like structure. We are trying to use this representation to characterize the "complexity" or "diversity" of the image structures in various ways.

In summary, the analysis of IRAS images carried out under this grant shows that panoramic, densely-sampled column density maps of regions of low-mass star formation reveals a complex structure which appears qualitatively different from standard concepts of interstellar clouds. The complex structure requires new methods of analysis. Structure trees, fractal dimension, and spectrum of singularities have been used to characterize this structure, with interesting implications for the physics of the interstellar medium and star formation.